Economic Losses of Carbon Emissions from Circum-Arctic Permafrost Regions under RCP-SSP Scenarios

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ABSTRACT: Under rapid Arctic warming, the vast amount of labile organic carbon stored in Arctic permafrost soils poses a potentially huge threat. Thawing permafrost will release hundreds of billion tons of soil carbon into the atmosphere in the form of CO_2 and CH_4 that would further intensify global warming and bring more challenges to human society. In this study, we use the PInc-PanTher model to estimate carbon emissions from thawing permafrost in the circum-Arctic during 2010-2100 followed by the PAGE09 integrated assessment model to evaluate the net economic losses caused by these permafrost carbon emissions. Our results show that in terms of net present value (NPV), the release of CO_2 and CH_4 from circum-Arctic permafrost will generate estimated net economic losses of US$2.5 trillion (5-95% range: 0.3-11.2 US$ trillion) under the RCP4.5-SPP1 scenario and US$12.7 trillion (5-95% range: 1.6-41.8 US$ trillion) under the RCP8.5-SPP3 scenario between 2010-2100, which are equivalent to c. 4.9% and 6.4% respectively of economic losses of global carbon emissions.

Keywords: Arctic permafrost; soil carbon emissions; economic impacts; RCP-SSP scenario.

■ INTRODUCTION

Permafrost, or perennially frozen soil, is soil that has a temperature lower than 0°C continuously for at least 24 consecutive months [1,2]. In the northern hemisphere, permafrost occurs in 24% of exposed land, equivalent to about 1.6-2.1×10^7 km^2 [3]. Permafrost is widely distributed in the northern high-latitude regions, including Siberia, Alaska, northern Canada, Greenland, parts of Russia and Scandinavia. It also appears in some alpine regions at high-altitude regions (e.g. the

Qinghai-Tibetan Plateau[4]) and some subsea regions below Arctic Ocean continental shelves (e.g. the East Siberian Arctic Shelf [5]).

The terrestrial permafrost carbon pool in the circum-Arctic permafrost regions is 1,330-1,580 Pg (1 Pg = 1 billion tons) [6], nearly double that in the atmosphere [7]. The buried organic carbon deposits have accumulated over thousands of years through dust deposition, alluvial sedimentation and peat development[8,9], and are to a great degree stabilized currently by being frozen or waterlogged [10]. Due to the Arctic amplification of global warming [11], continued warming in the 21st century will significantly increase the extent of permafrost degradation and lead to thickening of the active layer in summer periods. By 2200, the area of Arctic permafrost will be reduced by 29–59% and the thickness of the active layer will increase by 53–97 cm [12]. Although at present the carbon flux from permafrost soils into the atmosphere is minute relative to the whole permafrost carbon pool, thawing permafrost in the Arctic during the 21st century will release large amount of soil carbon in forms of CO_2 and CH_4 into the atmosphere, which can amplify the warming effect further (i.e. so-called permafrost carbon-climate feedback)[13]. Therefore, it is important to assess economic impacts of carbon emissions from the circum-Arctic permafrost region. In this study, we will use multi-model ensemble simulations, the PInc-PanTher model and the PAGE09 integrated assessment model to evaluate economic impacts of permafrost emissions during 2010-2100 under combined climate and socio-economic scenarios (RCP4.5-SSP1 and RCP8.5-SSP3).

METHODS

In order to assess economic impacts of CO_2 and CH_4 emissions from circum-Arctic permafrost regions, we will consider two kinds of future scenarios: Representative Concentration Pathways (RCPs) and Shared Socio-economic Pathways (SSPs). RCPs are consistent with a wide range of possible changes in future anthropogenic carbon emissions, and aim to represent their radiative forcing [14]. SSPs reflect the correlation between radiative forcing and socio-economic development and describe global development in the future [15]. According to the recommended combination for climate and socio-economic scenarios [16], in this study two combinations of future scenarios (namely, RCP8.5-SSP3 and RCP4.5-SSP1) are used. The RCP8.5-SSP3 scenario describes a gloomy future world that faces high challenges of climate change and is highly dependent on fossil fuels. It assumes little or no mitigation efforts, a fast growing population, a low rate of technology development and GDP growth, and a massive increase in world poverty. The RCP4.5-SSP1 scenario describes a sustainable development world with low climate change challenges and high mitigation costs. Emissions under RCP4.5 scenario peak around 2040, then decline. At the same time, global population peaks at nearly 8 billion in mid-century and then declines after. The per capita GDP in the SSP1 scenario is much higher than that of the SSP3 scenario.

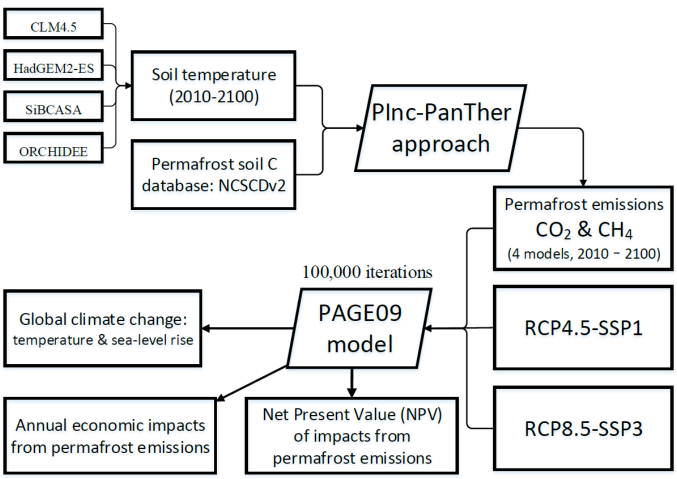

Figure 1 | Schematic diagram

We will use the known PInc-PanTher model [17] to evaluate the future permafrost emissions of CO_2 and CH_4 (Figure 1). It can provide a data-constrained approach to estimating the forced strength of the permafrost carbon response to Arctic warming, and to evaluating the sensitivity of permafrost carbon to global warming. The main inputs of the PInc-PanTher model are initial permafrost soil carbon (C) distribution and simulations of future soil thermal dynamics. In this study, we choose the Northern Circumpolar Soil Carbon Database Version 2 (NCSCDv2) [18] as the initial distribution of permafrost soil carbon. The future soil thermal dynamics are predicted by the ensemble of four climate models (Table 1) under RCP 4.5/8.5 scenarios. Compared to an individual model, multi-model ensembles can generally reduce uncertainty of prediction and provide higher accuracy and consistency [19,20]. Finally, since the percentage of methane emissions in total carbon emissions is observed as 2.3% [26], we use this proportion in simulations of the PInc-PanTher model.

Table 1. Four climate models used in this study [12,21-23]

Model acronym	Model name
CLM4.5	Community Land Model, Version 4.5
HadGEM2-ES	Hadley Centre Global Environmental Model 2-Earth System
SiBCASA	Simple Biosphere/Carnegie-Ames-Stanford Approach Model
ORCHIDEE-MICT	ORganizing Carbon and Hydrology In Dynamic EcosystEms-aMeliorated Interactions between Carbon and Temperature

Even with the same permafrost carbon emissions, the resultant economic losses may be different under different socio-economic scenarios combined with RCP emission scenarios. In this study, we use the Policy Analysis for the Greenhouse Effect 2009 (PAGE09) integrated assessment model [24] (Figure 1) to assess the economic impacts of permafrost carbon emissions under two combinations of future scenarios (namely, RCP8.5-SSP3 and RCP4.5-SSP1). The PAGE09 integrated assessment model includes four main modules: emission, climate, costs and economic impacts, which are organized sequentially. It can make many parametric analyses of social-economic-natural systems and is one of three models adopted by the U.S. government to estimate the social cost of carbon emissions [25]. The PAGE09 model links simulations of future climate change with resulting economic impacts, with consideration of mitigation, adaptation and costs. The economic impacts module in the PAGE09 model consist of four sectors (sea-level, economic, non-economic and discontinuities). The sea-level sector assess damages resulting from sea-level rise and related adaptation; the economic sector includes losses on climate sensitive sectors, extra energy expenditures and so on; the non-economic sector covers impacts on human health, ecosystems, leisure activities and so on; and the discontinuities sector represents the risk of abrupt change or catastrophe. In order to evaluate the net economic impacts of permafrost emissions, we input future permafrost carbon emissions predicted by the PInc-PanTher model into the PAGE09 model and ran 100,000 iterations for each socio-economic and emission scenario.

RESULTS

Driving the PInc-PanTher model by soil thermal dynamic data from simulations of four climate models (Table 1), we predict annual emissions of CO_2 and CH_4 in circum-Arctic permafrost regions under RCP4.5 and RCP8.5 scenarios during 2010-2100 (see Figure 2). Permafrost carbon emissions under the RCP4.5 scenario would peak around the middle of the century, then decrease gradually. Under the RCP8.5 scenario, permafrost emissions would continue to rise throughout the 21st century, and would be about twice as much as those under RCP4.5 in 2100. During 2010 to 2100, circum-Arctic permafrost regions will lose 21~46 Pg and 49~92 Pg of soil carbon storage under RCP4.5 and RCP8.5 scenarios, respectively.

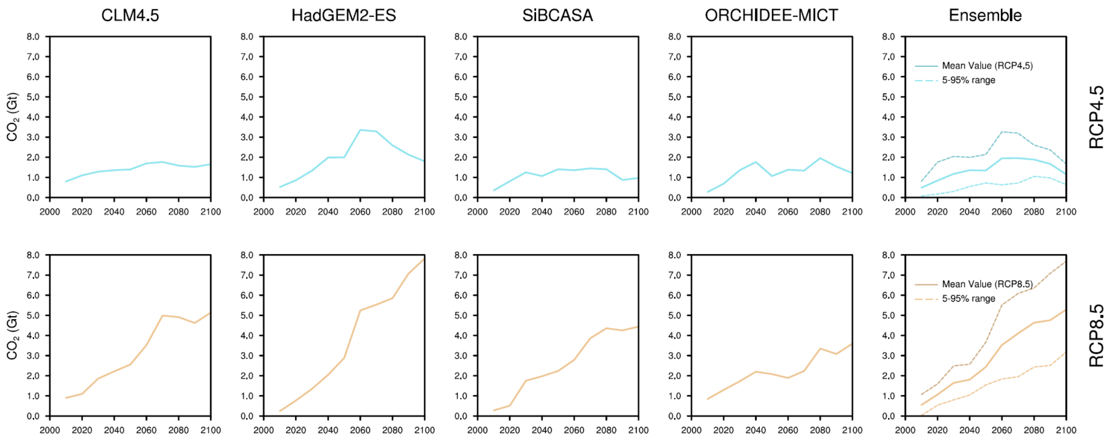

Figure 2 | Prediction of annual carbon emissions from thawing permafrost under RCP4.5 and RCP8.5 scenarios

Driving the climate module of the PAGE09 model using 2010-2100 permafrost carbon emissions predicted by the PInc-PanTher model and multi-model ensemble reveals that permafrost carbon emissions would further increase the global warming by an extra 0.09 °C (5–95% range: 0.06–

0.13 °C) under RCP 4.5 scenario and 0.13 °C (5–95% range: 0.8–0.18 °C) under RCP8.5 scenario (Figure 3). Compared with the RCP8.5 scenario, due to the lower global mean temperature rise, the additional negative impacts of thawing permafrost would be smaller under the RCP4.5 scenario.

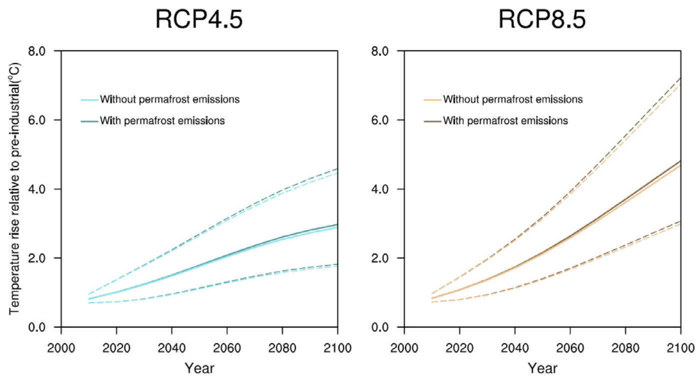

Figure 3 | Global mean temperature rise with/without permafrost carbon emissions under RCP4.5/8.5 scenarios based on simulations of the PAGE09 model. Solid lines represent the mean value of 100,000 simulations and dashed lines represent the 5-95% confidence interval.

Based on the outputs of the economic impacts module in the PAGE09 model driven by the combination of the PInc-PanTher model and each climate model (or multi-model ensemble), we evaluated annual economic losses of permafrost CO_2 and CH_4 emissions (Figure 4). Predictions driven by the HadGEM2-ES model reveal greater economic losses, while predictions driven by the other three models are similar. These are consistent with differences in predicted annual CO_2 emissions from thawing permafrost by using the combination of the PInc-PanTher model and different climate models (Figure 2). Due to nonlinear interactions and uncertainties of the physical processes and economic impacts of climate change, such as the parameterization of feedback response time and transient climate response, the uncertainty range of predicted annual economic losses is relatively wide.

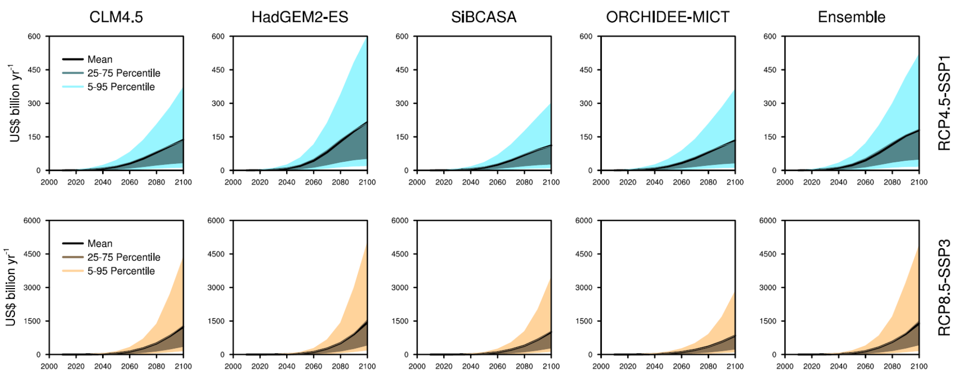

Figure 4 | Predicted annual economic losses of permafrost emissions under RCP4.5-SSP1 and RCP8.5-SSP3 scenarios. Black lines represents the mean values, the light and dark color intervals show 5-95% and 25-75% confidence intervals, respectively.

The growth rate of annual economic losses of permafrost carbon emissions is predicted to be halved every 30 years under both RCP4.5-SSP1 and RCP8.5-SSP3 scenarios. In detail, for three time periods: 2010-2040, 2040-2070 and 2070-2100, it will take about 5, 10 and 20 years respectively to double economic losses. Moreover, the economic losses would grow faster under the RCP8.5-SSP3 scenario than that under the RCP4.5-SSP1 scenario. In 2100, the ensemble mean of economic losses of permafrost carbon emissions would be nearly US$0.18 trillion under RCP4.5-SSP1 scenario (about 0.04% of projected global GDP in 2100). The 5–95% confidence interval ranges from 0.02 to 0.53 US$ trillion, and the 25–75% confidence interval ranges from 0.05 to 0.18 US$ trillion. Under the RCP8.5-SSP3 scenario, the ensemble mean of economic impacts of thawing permafrost would be nearly US$1.39 trillion in 2100 (about 0.49% of projected global GDP in that year), and the 5–95% confidence interval ranges from 0.17 to 4.97 US$ trillion, the 25–75% confidence interval ranges from 0.43 to 1.51 US$ trillion. This means that in 2100, the economic losses of carbon emissions from permafrost carbon emissions under RCP8.5-SSP3 scenario are about 7.7 times greater than those under the RCP4.5-SSP1 scenario.

Finally, we discount net economic impacts during 2010-2100 back to the base year 2010, considering the time value of money and losses in utility. This calculation is based on the discount rate, and the cumulative sum of discounted annual impacts, called the net present value (NPV) [27]. We estimate the cumulative probability distribution of net economic impacts of permafrost emissions in terms of NPV (Figure 5). Under the RCP4.5-SSP1 scenario, the mean NPV of economic losses due to carbon emissions from thawing permafrost in the circum-Arctic regions is US$2.5 trillion. The mean NPV will increase to US$12.7 trillion when we consider the RCP8.5-SSP3 scenario, about five times than that under the RCP4.5-SSP1 scenario. In terms of uncertainty, under the RCP4.5-SSP1 scenario, the 5-95% confidence interval ranges from 0.3 to 11.2 US$ trillion, while under the RCP8.5-SSP3 scenario, the 5-95% confidence interval ranges from 1.6 to 41.8 US$ trillion. Based on predictions by the PAGE09 model, the mean NPV of economic losses of global carbon emissions is US$51.1 trillion and US$197.6 trillion under RCP4.5-SSP1 and RCP8.5-SSP3 scenarios, respectively. Therefore, permafrost carbon emissions contribute about 4.9% and 6.4% of economic losses of global carbon emissions, respectively.

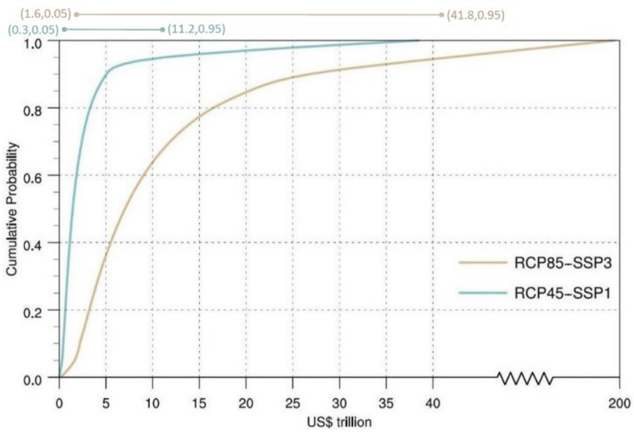

Figure 5 | Cumulative distribution function of the net present value (NPV) of economic losses of permafrost carbon emissions during 2010 to 2100. Color bars at the top of the figure represent the 5 and 95% confidence intervals for two scenarios.

Conclusions and Discussion

Permafrost in the circum-Arctic is very sensitive to global warming. Although at present the carbon flux from permafrost soils into the atmosphere is minute relative to the whole permafrost carbon pool, in the 21st century, thawing permafrost in the circum-Arctic will release large amounts of soil carbon in forms of CO_2 and CH_4 into the atmosphere. Hope and Schaefer's previous research in Nature Climate Change [29] estimated that, by 2200, the release of CO_2 and CH_4 into the atmosphere from the circum-Arctic permafrost region would increase the net present value of economic losses by US$3–166 trillion (5–95% range, mean US$43 trillion). However, their estimate was based on the outdated IPCC SRES A1B emissions scenario, and used a single process-based model (SiBCASA) to simulate the permafrost carbon dynamics. In this study, our assessment is based on a multi-model ensemble and two combined future scenarios (RCP4.5-SSP1 and RCP8.5-SSP3), which provides more reliable projections for future social-economic impacts. Moreover, the projected permafrost emissions in this study are derived from the better PInc-PanTher model and the latest version of observed permafrost carbon database NCSCDv2. Our results indicate that during 2010 to 2100, the circum-Arctic permafrost carbon stock will lose 21~46 Pg under the RCP4.5 scenario and 49~92 Pg under the RCP8.5 scenario, and that these carbon emissions would increase the global warming by an extra 0.09 °C under RCP4.5 scenario and 0.13 °C under RCP8.5 scenario. It means that an aggressive mitigation strategy on anthropogenic carbon emissions can reduce extra carbon emissions and related warming due to thawing permafrost. In 2100, the annual economic losses of permafrost emissions is US$0.18 trillion (about 0.04% of projected global GDP in 2100) under RCP4.5-SSP1 scenario, and US$1.39 trillion (about 0.49% of projected global GDP in 2100) under RCP8.5-SSP3 scenario. In terms of net present value (NPV), between 2010-2100, the mean NPV of economic losses would be US$2.5 trillion and US$12.7 trillion under RCP4.5-SSP1 and RCP8.5-SSP3 scenario, respectively, which are equivalent to 4.9% and 6.4% of economic losses of global carbon emissions during 2010-2100, respectively. Compared with these two scenarios, this reveals that an effective carbon abatement strategy can reduce economic losses of permafrost emissions by about US$10.2 trillion.

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REFERENCES

[1] Harris, S. A., French, H. M., Heginbottom, J. A., Johnston, G. H., Ladanyi, B., & Sego, D. C., et al. (1988). Glossary of permafrost and related ground-ice terms. Arctic & Alpine Research, 21(2).

[2] Dobinski, W. (2011). Permafrost. Earth-Science Reviews, 108(3), 158-169.

[3] Gruber, S. (2011). Derivation and analysis of a high-resolution estimate of global permafrost zonation.

Cryosphere Discussions, 5(3), 1547-1582.

[4] Wang, B., & French, H. M. (2010). Climate controls and high-altitude permafrost, qinghai-xizang (tibet) plateau, china. Permafrost & Periglacial Processes, 5(2), 87-100.

[5] Shakhova, N., Semiletov, I., Gustafsson, O., et al. (2017). Current rates and mechanisms of subsea permafrost degradation in the east siberian arctic shelf. Nature Communications, 8(7).

[6] Schuur E. A. G., Mcguire A. D., Schädel, C., et al. (2015). Climate change and the permafrost carbon feedback. Nature, 520(7546), 171.

[7] Zimov, S. A., Schuur, E. A. G., & Chapin, F. S. (2006). Permafrost and the global carbon budget. Science, 312(5780), 1612-1613.

[8] Tarnocai, C., Canadell, J. G., Schuur, E. A. G., Kuhry, P., Mazhitova, G., & Zimov, S. (2009). Soil organic carbon pools in the northern circumpolar permafrost region. Global Biogeochemical Cycles, 23(2).

[9] Schuur, E. A. G., Bockheim, J., Canadell, J. G., et al. (2008). Vulnerability of permafrost carbon to climate change: implications for the global carbon cycle. Bioscience, 58(8), 701-714.

[10] Bracho, R., Natali, S., Pegoraro, E., et al. (2016). Temperature sensitivity of organic matter decomposition of permafrost-region soils during laboratory incubations. Soil Biology & Biochemistry, 97, 1-14.

[11] Cohen, J., Screen, J. A., Furtado, J. C., Barlow, M., Whittleston, D., & Coumou, D., et al. (2014). Recent arctic amplification and extreme mid-latitude weather. Nature Geoscience, 7(9), 627-637.

[12] Schaefer, K., Zhang, T., Bruhwiler, L., & Barrett, A. P. (2011). Amount and timing of permafrost carbon release in response to climate warming. Tellus, 63(2), 165-180.

[13] Macdougall, A. H., Avis, C. A., & Weaver, A. J. (2012). Significant contribution to climate warming from the permafrost carbon feedback. Nature Geoscience, 5(10), 719-721.

[14] Vuuren, D. P. V., Edmonds, J., Kainuma, M., Riahi, K., Thomson, A., & Hibbard, K., et al. (2011). The representative concentration pathways: an overview. Climatic Change, 109(1-2), 5.

[15] O'Neill, B. C. et al. (2014). A new scenario framework for climate change research: The concept of shared socioeconomic pathways. Climatic Change, 122, 387–400.

[16] Kriegler, E., O'Neill, B. C., Hallegatte, S., et al. (2012). The need for and use of socio-economic scenarios for climate change analysis: a new approach based on shared socio-economic pathways. Global Environmental Change, 22(4), 807-822.

[17] Koven, C. D., Schuur, E. A., Schädel, C., et al. (2015). A simplified, data-constrained approach to estimate the permafrost carbon-climate feedback. Philosophical Transactions, 373(2054), 20140423.

[18] Hugelius, G., Strauss, J., Zubrzycki, S., et al. (2014). Estimated stocks of circumpolar permafrost carbon with quantified uncertainty ranges and identified data gaps. Biogeosciences,11,23(2014-12-01), 11(23), 6573– 6593.

[19] McGuire AD, et al. (2016) Variability in the sensitivity among model simulations of permafrost and carbon dynamics in the permafrost region between 1960 and 2009. Global Biogeochem Cycles 30:1015–1037.

[20] Martre, P., Wallach, D., Asseng, S., et al. (2015). Multimodel ensembles of wheat growth: many models are better than one. Global Change Biology, 21(2), 911-925.

[21] Oleson KW et al. (2013). Technical description of version 4.5 of the Community Land Model(CLM). NCAR Technical Note. National Center for Atmospheric Research, Boulder, CO, USA.

[22] Jones, C. D., Hughes, J. K., Bellouin, N., et al. (2011). The hadgem2-es implementation of cmip5 centennial simulations. Geoscientific Model Development, 4(3), 543-570.

[23] Krinner G, Viovy N, de Noblet-Ducoudre N, et al. (2005). A dynamic global vegetation model for studies of the coupled atmospherebiosphere system. Glob. Biogeochem. Cycles 19, GB1015.

[24] Hope, C. (2011). The social cost of CO_2 from the PAGE09 model. Social Science Electronic Publishing.

[25] Diaz, D., & Moore, F. (2017). Quantifying the economic risks of climate change. Nature Climate Change, 7(11), 774-782.

[26] Schuur, E. A. G., Bockheim, J., Canadell, J. G., et al. (2008). Vulnerability of permafrost carbon to climate change: implications for the global carbon cycle. Bioscience, 58(8), 701-714.

[27] Storesletten, K. (2010). Fiscal implications of immigration: a net present value calculation. Scandinavian Journal of Economics, 105(3), 487-506.

[28] Mcguire, A. D., Lawrence, D. M., Koven, C., et al. (2018). Dependence of the evolution of carbon dynamics in the northern permafrost region on the trajectory of climate change. Proceedings of the National Academy of Sciences of the United States of America, 115(15), 3882-3887.

[29] Hope, C., & Schaefer, K. (2016). Economic impacts of carbon dioxide and methane released from thawing permafrost. Nature Climate Change, 6(1), 56.